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Wireless Vital Sign Sensor Network Simulations for Mass Casualty Response

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Interim Report

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Analysis of the needs of a US Air Force Pararescue Program has determined that there is a need for improved monitoring of injured persons during the initial stages of rescue operations. Simulations of wireless sensor networks were used to investigate the potential for performance improvements that can be gained through various forms of multi-hop networking.

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Wireless Medical Sensors, Mobile Adhoc Network, Mass Casualty, Network Simulation

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1.0 TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 SUMMARY

Analysis of the needs of a US Air Force Pararescue Program has determined that there is a need for improved monitoring of injured persons during the initial stages of rescue operations. This need stems from real world observation of both combat and non-combat rescue scenarios.

The requirements of monitoring systems for use in rescue operations are nearly identical to those of civilian mass-casualty emergencies. The underlying problem in both situations is one of insufficient numbers or responders to treat the numbers and nature of the casualties. The techniques employed in these scenarios focus not strictly on treating the most severe casualties, but in efficiently dividing resources so that as many lives can be saved as possible. Treatment of those casualties with the most life threatening conditions may often be delayed in favor of rescuing casualties with less severe injuries.

This research investigates the impact that different methods of multi-hop networking may have in providing responders with timely vital sign data for large numbers of casualties. This is accomplished through a mobile adhoc network (MANET) simulation of an imagined body-mounted sensor platform that provides several basic vital sign signals. This facilitates further development of a functional system by identifying the strengths and weaknesses of different multi-hopping techniques and provides insight into which characteristics lead to the most resilient and reliable systems for casualty rescue.

This research was heavily influenced by findings from the CodeBlue project developed by Harvard Sensor Networks Lab [1], the Advanced Health and Disaster Aid Network [2], and the WIISARD SAGE Project [3].

2.0 INTRODUCTION

The requirements of the monitoring systems must be compatible with the rescue techniques and procedures employed. In comparison to traditional patient monitors, they must be lighter weight, wireless and battery-powered and they should provide a limited amount of high value information that can increase the situation awareness of the lead responders.

A wide variety of sensor types can provide value in a mass casualty operation and it is easy to overlook those sensors which provide the greatest value in favor of those that are frequently associated with medical operations. Two of the most important pieces of information that are often overlooked are the need for localization and the need to capture and organize the diagnosis performed by the responders. The former helps facilitate the prioritization of rescue individuals as they are treated and evacuated. The latter captures the opinions of the trained responder, usually in the form of a triage tag. While vital sign signals are valuable, particularly in the need to capture trending data, the analysis of a trained professional with the ability to visually inspect the nature and severity of an injury is far more critical. Of particular interest are sensors that can provide updates on temperature, respiration rate, and circulation parameters such as blood oxygen saturation and heart rate at regular intervals.

Limiting the total payload of data that needs to be transferred between casualty and responder allow for several design trades that could enhance the reliability of the system including a wider variety of wireless technology options and the possibility to use multi-hop routing techniques.

Sensors that produce continuous streams of unprocessed data, such as an electrocardiogram, would be used only when necessary during a mass casualty event. Not only would they consume too many precious network resources, but the analysis of the signals requires a high level of attention from responders and can reduce situation awareness. This can be particularly detrimental in combat rescue scenarios when additional emphasis is placed on expeditiously removing casualties from harm's way in order to prevent additional casualties.

The simulation described here used the TinyOS 2.x simulator (TOSSIM) to simulate the transmission of vital sign data between multiple casualties and multiple responders. TinyOS was chosen because it incorporates the means to use many multi-hop routing techniques and it is used with IEEE 802.15.4 hardware, which represents a reasonable and popular choice for vital sign sensors.

Additionally, the simulation was designed to account for the absorptive effect of the body and mobility. All vital signs were collected and sent from a single node every 10 seconds and the results were evaluated in respect to their ability to enhance responder situation awareness by reliably delivering data in a timely manner.

3.0 METHODS, ASSUMPTIONS, AND PROCEDURES

3.1 Simulation Parameters

A series of scenarios were constructed following an analysis of rescue procedures. Depending on the threat environment, vital sign monitors may need to be applied upon initial contact with an injured person and will likely be needed throughout all phases of triage until the casualty is evacuated from the site. One scenario was manually constructed to test communication representative of casualties closely grouped at a casualty collection point. Other scenarios with random distributions of 10 to 35 casualties were constructed for mass casualties to simulate the unpredictable nature of rescue scenarios. Additionally a scenario representing large scale casualty event was modeled using a random distribution of 100 casualties with multiple response teams. The following is a description of these scenarios

- Figure 1 depicts a group of nine closely spaced casualties as might be encountered at a casualty collection point. In many of these types of situations, security takes priority over medical treatment of the wounded, so it assumed that only two responders are available to provide medical care during triage.
- Figure 2 depicts a randomly generated group of casualties over a 50 m by 50 m field. Several of these are generated for analysis. Casualty numbers range from 10 to 35 in accordance with the design goals of our program. The response team is comprised of a centrally located team leader and 4 to 6 other responders.
- Figure 3 depicts an extreme mass casualty or disaster event with 100 casualties randomly distributed over a 200 m by 200 m field. Four response teams are present and the team leaders have portioned the field into quarters. Each responder is with a randomly selected casualty. This test case is represents a design requirement in excess of the program goals, but will provide additional information in stress testing the systems.

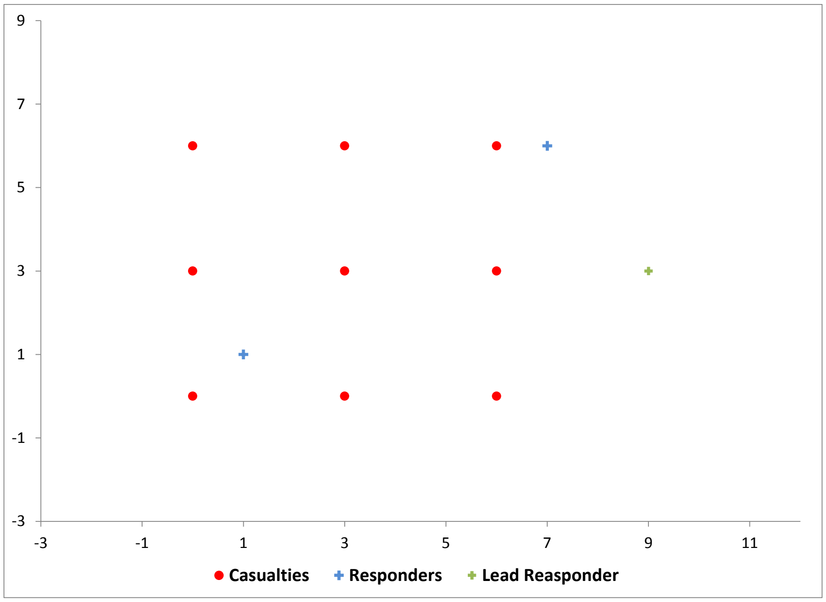

Figure 1. Closely Spaced Casualties With Three Rescue Personnel

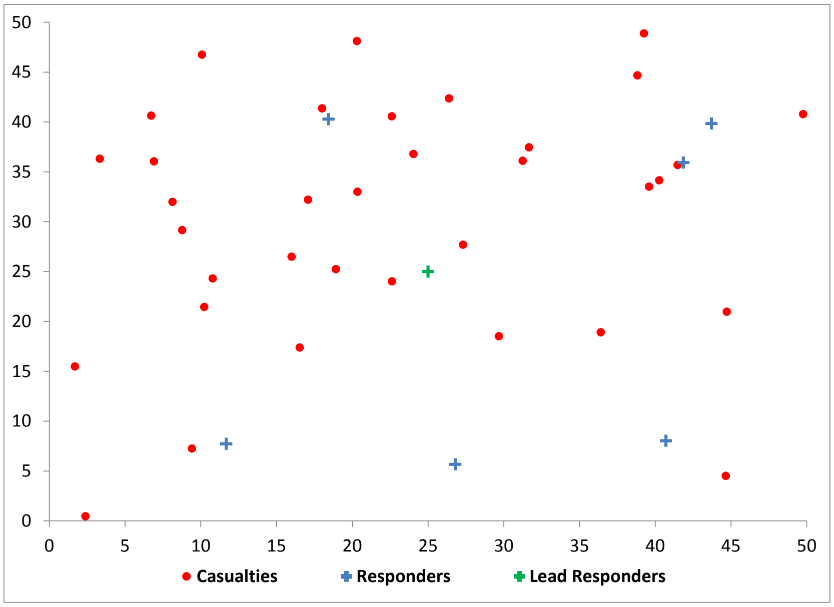

Figure 2. Example Randomly Distributed Casualties Over 50 x 50 Meter Area

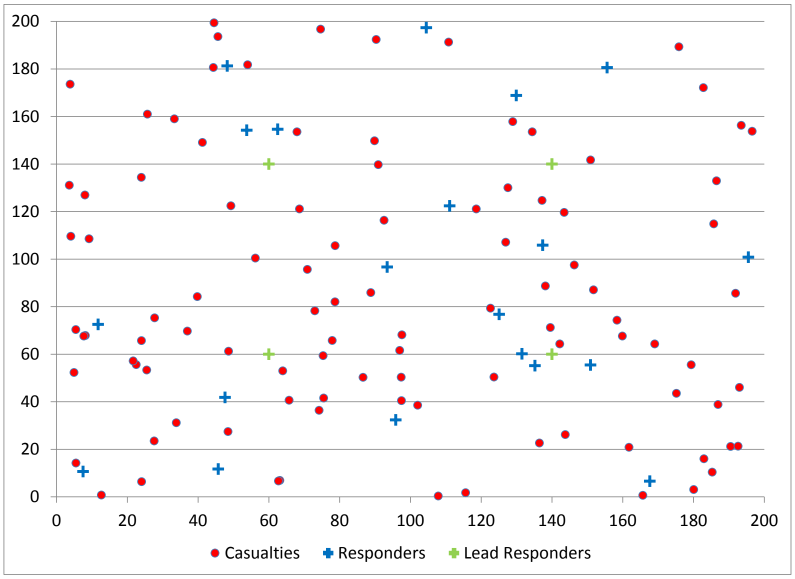

Figure 3. Example of 100 Randomly Distributed Casualties Over 200 x 200 Meter Area with Multiple Response Teams

Table 1 shows the complete list of tested conditions and the designated identifier. For all of these scenarios, path loss/gains between all devices needs to be estimated based on the distance between node locations. Performing this estimation requires some assumptions be made with respect to the final hardware. TOSSIM assumes that the model uses the MICAz wireless sensor which is available from MEMSIC. The MICAz incorporates a Texas Instruments CC2420 radio. This radio is also used on the MEMSIC TELOSB platform which has very similar RF characteristics. The performance of these two systems is well documented in research and provides conservative performance parameters for future wireless mote systems.

TOSSIM requires that each node to node link be described by a gain value. This is obtained through the Log Distance Path Loss Model which can be generalized from [4].

$$\boldsymbol{P = -10\, n\, \log_{10}(d) + A} \tag{1}$$

Where A is the gain offset for a distance of 1 meter. For the CC2420 radio, Texas Instruments specifies a loss of -45 dBm when used with the default transmission power of 0 dBm [5]. These simulations use the default transmission power, but elect for a more conservative gain offset of -48 dBm as verified in [6]. The path loss exponent, n, varies with environment. Use of the model has been validated in both indoor and outdoor environments in [7] and [6]. An ideal configuration such as a long corridor can be modeled using $n = 2$, whereas a typical indoor environment without wall obstructions may be best modeled with $n = 2.8$ [7]. Outdoor spaces can vary greatly produced path losses of $n = 2.1$ [7] and $n = 2.3$ [6] to n=3.5 [8]. The simulations use the path loss exponent of 2.3.

Additionally the simulation can be enhanced through modification of the noise floor. One approach to this is to use a worst case indoor environment with heavy wireless 802.11b usage. For 802.15.4 solutions, this often represents the worst case. TinyOS includes a noise model that is representative of this type of environment in noise readings taken at the Stanford University Meyer Library [9]. However, it should be recognized that this type of noise environment may be an exceptional case that would most likely apply only to indoor and urban environments and these simulation do not address many of the other wireless communication issues that would be associated with an indoor environment and for that reason it is best to model a challenging outdoor environment for these scenarios. A model using Gaussian distributed noise floor with a mean of -97 dBm and a standard deviation of 2 dBm was selected. A singular simulation is performed using the noise readings from the Meyer Library in order to demonstrate the effects of increased RF noise.

Table 1. Simulation Conditions and Identifiers

Test Condition Identifier	Description
C1_STATIC	Stationary nodes at collection point; 9 casualties, 2 responders, 1 lead responder
C2_MOBILE	Mobile nodes moving at 1 m/s; 50 x 50 meter map; 25 casualties, 4 responders, 1 lead responder
C3_MOBILE_SPARSE	Same as C2_MOBILE with 10 casualties, 2 responders, 1 lead responder
C4_MOBILE_DENSE	Same as C2_MOBILE with 35 casualties, 6 responders, 1 lead responder
C5_MOBILE_SLOW	Same as C2_MOBILE with node speed set to 0.25 m/s
C6_MOBILE_NOISY	Same as C2_MOBILE with noise readings from Stanford Meyer Library
C7_MOBILE_LARGE	Mobile nodes; 250 x 250 meter map; 100 casualties, 20 responders, 4 lead responders

Finally, the model should be modified to accommodate the effect caused by the human body. It is reasonable to assume that medical sensors would be attached to the upper body of a patient. Most likely, the head, neck, chest or arm. Ideally, this simulation would be able to account for casualties in the prone position; however, information to accommodate this in simulation has not been located in existing literature. This simulation will assume that all casualties are in an upright position with a chest mounted sensor and rely on data that can be gathered from [10]. Table 2 shows the propagation losses caused by the proximity of the human body. Intermediate losses between the values in the table were computed by interpolation.

In the case of communication between nodes mounted on separate bodies, the path loss model was modified to incorporate the costs caused by each body

$$\boldsymbol{P = -10\, n\, \log_{10}(d) + A + BodyCost1(\theta_1) + BodyCost2(\theta_2)} \qquad (2)$$

Simulations were run for 3700 seconds. In all but one simulation nodes would move at a speed of 1 m/s in the direction of a random waypoint, with a new waypoint being generated every 30 seconds. A node did not stop if the waypoint was reached but continued through the point and continued to travel with the same heading. During all path loss calculations, it was assumed that the body was facing in the direction of travel. The location of the node representing lead responders remained stationary and changed its heading every 30 seconds. In one simulation, the speed was slowed to 0.25 m/s and new waypoints were generated every 120 seconds.

Table 2. Propagation Losses Due to Body (0 degrees is Forward from Body)

Angle (degrees)	Loss (dBm)
0	-7
60	-7
120	-17
180	-27
240	-17
300	-7
360	-7

3.2 Sensor Emulation

The simulation was designed to represent nodes that passed along very limited amounts of data needed to describe the most basic vital signs of a casualty. Vital signs such as temperature, blood oxygen saturation, heart rate, and blood pressure were considered. It was assumed that all of these vital signs could be represented in a 10 byte message structure. This message was sent by every node, every 10 seconds. Nodes were booted at random intervals between 1 and 10 seconds.

3.3 Protocol Implementations

Four separate protocols were simulated to observe how the varying characteristics of each led to different outcomes. The first, termed "Broadcast" was designed to have each node broadcast its message and incorporated no more advanced networking features. The second, termed "Flood", once again had each node broadcast its message, but also incorporated a simple flood based architecture in which listening nodes would repeat any message that they had not previously received. Many flooding techniques incorporate random back-off timers to avoid contention when rebroadcasting. This implementation did not. The third, termed "DYMO", used the Dynamic MANET On-demand Routing Protocol (DYMO) implementation that is included with TinyOS, TYMO. The fourth, termed Dissemination used the Designated Relays Inquiry Protocol (DRIP) Dissemination protocol included in TinyOS.

DYMO was selected for investigation because it represents a class of routing algorithms which rely on background activities to collect and update information regarding available routes and varying techniques for route maintenance and discovery. Other popular examples include Adhoc on Demand Distance Vector (AODV), and Dynamic Source Routing (DSR). The fact that DYMO is considered to be a successor to AODV with changes designed to make the system more tolerant of mobility made it particularly appealing because AODV is nearly identical to the routing protocol used in ZigBee products. Since ZigBee software stacks are widely available and since a standard exists for ZigBee use in healthcare, it is a very appealing option for wireless system designers. The performance of DYMO, which is more suited for mobile applications, in many ways represents a best case for ZigBee and other similar products. DYMO is excluded from some simulations and evaluations. The design of the protocol requires that each sensor node be aware of the monitoring node addresses. This presents two problems. First, DYMO is not multicast, so each node needs to individually send messages to each receiving node. Second, since each sender needs to know the destination addresses, it would be impractical to implement this protocol in a scheme where monitoring node numbers and addresses are not predetermined, so the DYMO is only be evaluated in its ability to deliver sensor data to a single monitoring station and is excluded from all evaluations involving multiple monitoring stations.

Dissemination was chosen as a representative of routing protocols that implement various forms of delay tolerant networking (DTN). Nodes use a store and forward approach to sending messages. The WIISARD SAGE project demonstrated that a custom designed routing protocol which incorporated DTN approaches was much more successful in transferring triage tag type of data to responders [3]. Vital sign needs to be transferred to the closest responders in a more timely fashion than tag data in order to illicit a quick response when needed. Dissemination was chosen in order to investigate the suitability of DTN protocols for providing frequent updates to nearby responders while allowing for increased delay in transferring information to more distant responders.

4.0 RESULTS AND DISCUSSION

The simulations provided time information data from which message sent and received times by disparate nodes could be determined. This information needed to be condensed into a metric that would be indicative of the responders experience with the device. The responders are primarily interested in facilitating the situation awareness of the lead responder in monitoring for changing patient vital signs by improving data availability. Data availability will be enhanced in this case by ensuring the timeliest delivery of sensor data. The level of situation awareness is directly related to the lag time between successive updates for each patient. In order to assess the reliability of the simulated systems in elevating situation awareness, it is therefore necessary to quantify the lag experienced by the lead responder in observing the vital signs by each patient.

Figure 4 shows the results that were generated for the C2_MOBILE condition. This can then be used to evaluate on a percentile basis, the system’s ability to deliver data at a rate greater than the independent time variable. For example, if the desire is for data lag to be no greater than 25 seconds, then Figure 4 can be used to determine that a system equipped with Dissemination would provide the responder with this level of performance 82% of the time and would fail to perform to this level 18% of the time.

Results for all conditions were evaluated in this manner by evaluating the distribution curves at lag times of 25, 55, and 115 seconds. The degree to which they failed to perform is summarized in Table 3.

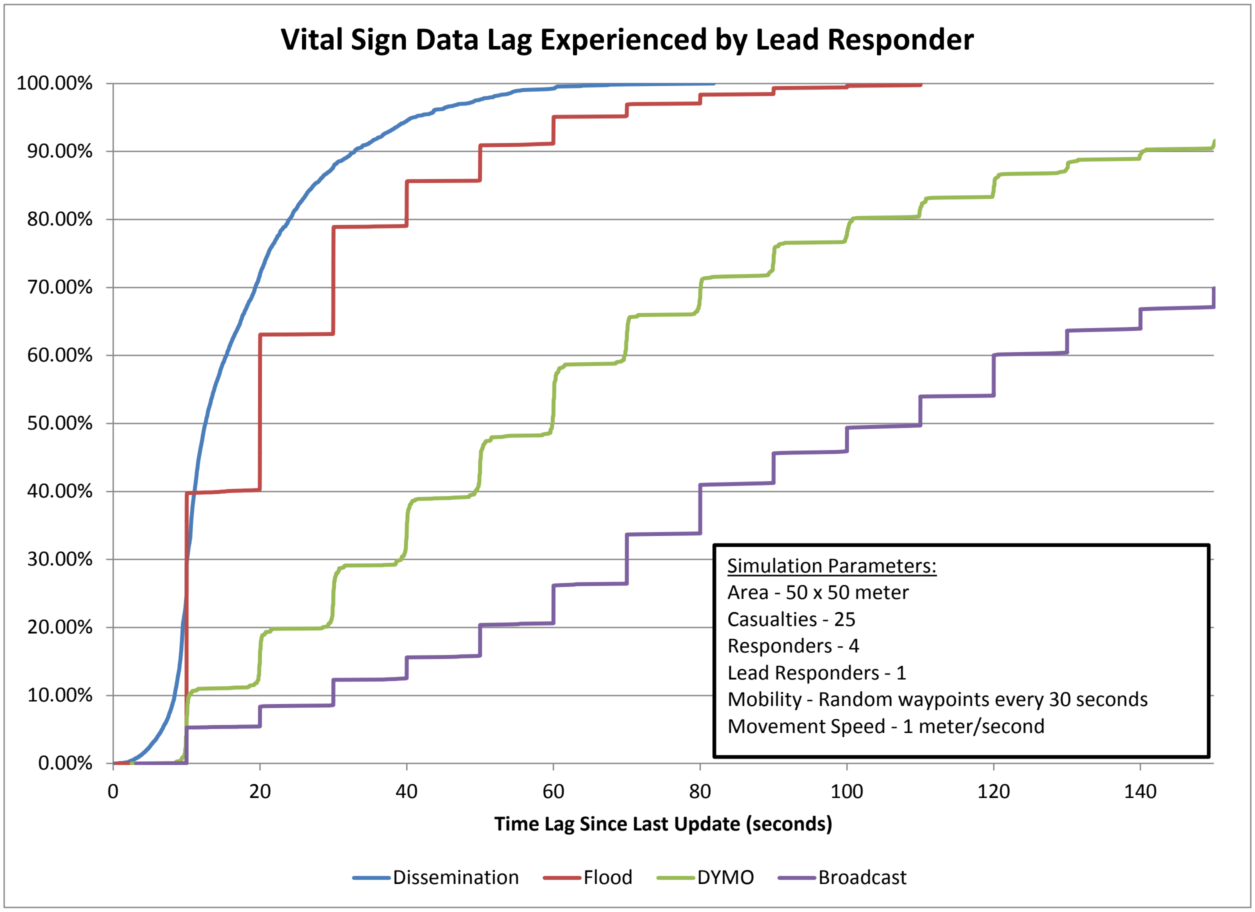

Figure 4. Simulation Results for the Basic Mobile Simulation

Table 3. Summary of Simulations with Lag CDF Values at 25, 55 and 115 Second Times

Parameters	Test Condition	Collection Level	% casualty data lagging > 25 seconds	% casualty data lagging > 55 seconds	% casualty data lagging > 115 seconds
Broadcast	C1_STATIC	Any Responder	5%	1%	0%
		Lead Responder	13%	7%	2%
	C2_MOBILE	Any Responder	66%	33%	5%
		Lead Responder	91%	79%	46%
	C3_MOBILE_SPARSE	Any Responder	80%	57%	13%
		Lead Responder	92%	82%	47%
	C4_MOBILE_DENSE	Any Responder	56%	22%	2%
		Lead Responder	92%	79%	43%
	C5_MOBILE_SLOW	Any Responder	62%	53%	36%
		Lead Responder	88%	84%	78%
	C6_MOBILE_NOISY	Any Responder	74%	52%	24%
		Lead Responder	89%	75%	55%
	C7_MOBILE_LARGE	Any Responder	91%	80%	57%
		Lead Responder	99%	98%	94%
Dissemination	C1_STATIC	Any Responder	0%	0%	0%
		Lead Responder	0%	0%	0%
	C2_MOBILE	Any Responder	15%	1%	0%
		Lead Responder	18%	1%	0%
	C3_MOBILE_SPARSE	Any Responder	45%	9%	0%
		Lead Responder	55%	13%	0%
	C4_MOBILE_DENSE	Any Responder	9%	0%	0%
		Lead Responder	11%	0%	0%
	C5_MOBILE_SLOW	Any Responder	24%	13%	4%
		Lead Responder	41%	17%	4%
	C6_MOBILE_NOISY	Any Responder	26%	5%	0%
		Lead Responder	37%	8%	0%
	C7_MOBILE_LARGE	Any Responder	64%	38%	15%
		Lead Responder	85%	55%	21%
DYMO	C1_STATIC	Lead Responder	30%	7%	2%
	C2_MOBILE	Lead Responder	80%	52%	17%
	C3_MOBILE_SPARSE	Lead Responder	90%	77%	45%
	C4_MOBILE_DENSE	Lead Responder	84%	59%	26%
	C5_MOBILE_SLOW	Lead Responder	85%	61%	39%
	C6_MOBILE_NOISY	Lead Responder	98%	96%	92%
Flood	C1_STATIC	Any Responder	7%	2%	0%
		Lead Responder	8%	3%	0%
	C2_MOBILE	Any Responder	27%	5%	0%
		Lead Responder	37%	9%	0%
	C3_MOBILE_SPARSE	Any Responder	68%	36%	5%
		Lead Responder	78%	50%	13%
	C4_MOBILE_DENSE	Any Responder	18%	2%	0%
		Lead Responder	24%	4%	0%
	C5_MOBILE_SLOW	Any Responder	34%	20%	7%
		Lead Responder	54%	28%	9%
	C6_MOBILE_NOISY	Any Responder	66%	40%	16%
		Lead Responder	78%	60%	38%
	C7_MOBILE_LARGE	Any Responder	81%	64%	41%
		Lead Responder	97%	95%	85%

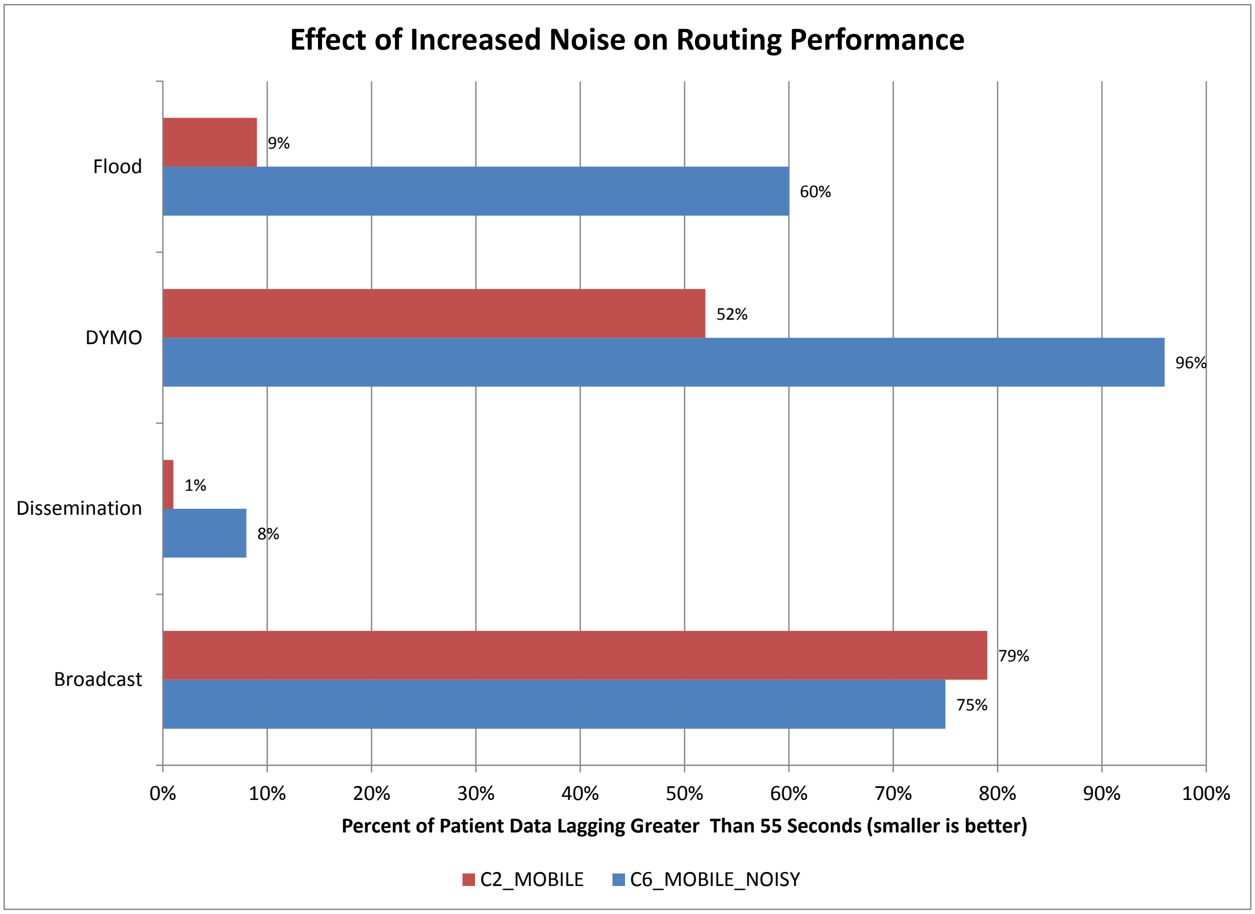

Figure 5. The Effect of Increased Noise on Routing Method Performance

5.0 CONCLUSIONS

The results are best interpreted in a benchmark style that compares the abilities of each routing method under a specific test condition.

Figure 5 illustrates the degradation caused in a high noise environment. The basic Broadcast method was only slightly degraded, but the simple Flood protocol which extended Broadcast with a forwarding scheme showed a high level of performance degradation. In fact, the noise nearly eliminated any benefit of multi-hopping in this simplistic method. DYMO showed extremely poor performance. This is not entirely surprising as the protocol relies on large amounts of background messaging to create routes that are a necessary precursor to sending messages. The Dissemination protocol shows resiliency. The opportunistic approach to spreading information increases the likelihood that data flow continues through the network by adjusting around those time periods in which noise levels are higher.

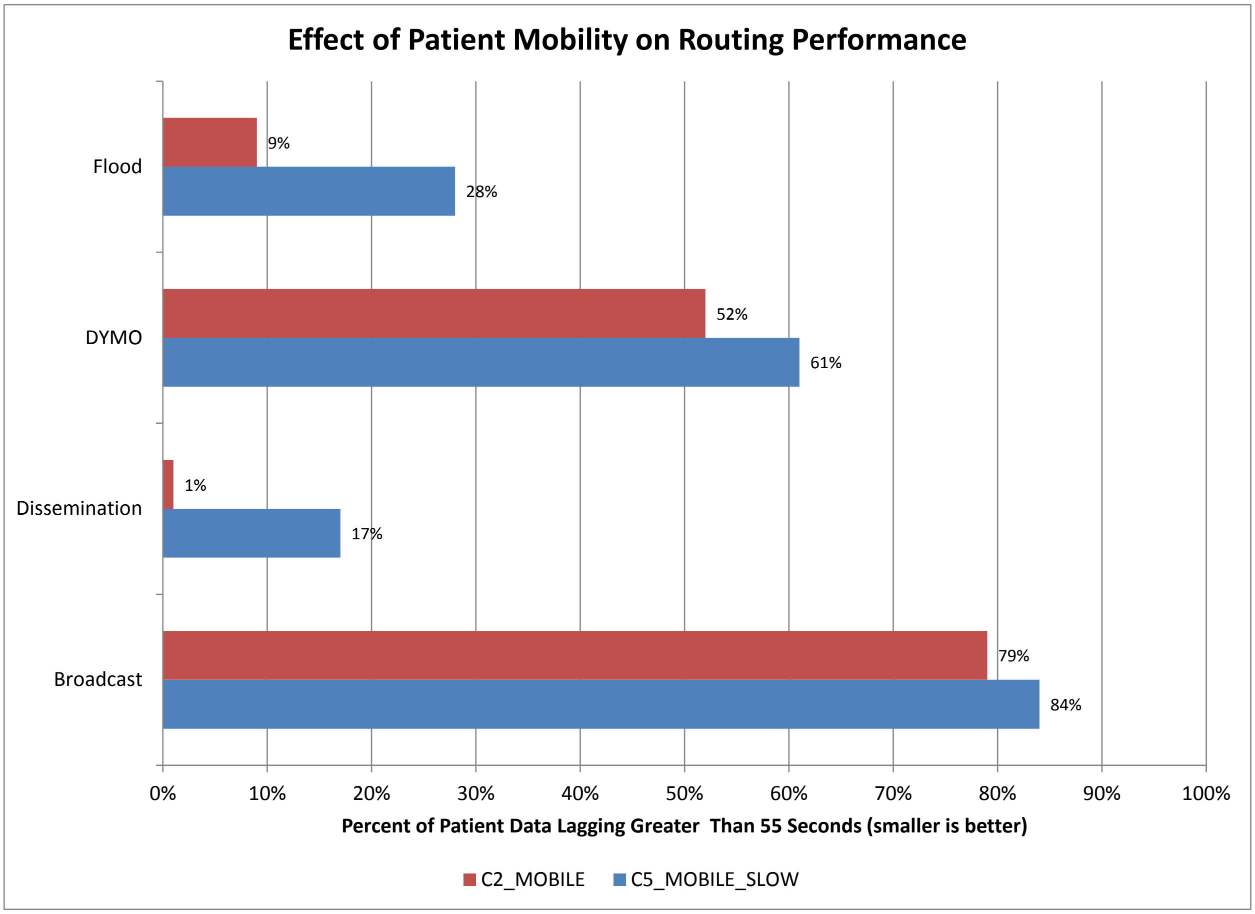

Figure 6. Effect of Patient Mobility on Routing Method Performance

Figure 6 illustrates the effects of patient and responder mobility. It is intuitive that greater movement will increase the chances of two nodes successfully transmitting data over multiple attempts. The normal mobile simulation moved nodes at 1 m/s and the C2_MOBILE_SLOW condition moved the nodes at 0.25 m/s. However, the Broadcast benchmark shows that the gains are marginal in the case of a single-hop transmission. What is most interesting is that Flood and Dissemination, which are consistently the best performing protocols, derive a disproportional benefit from mobility. This is an indicator the relative importance of flooding style approaches as well as the potential impacts of data-muling.

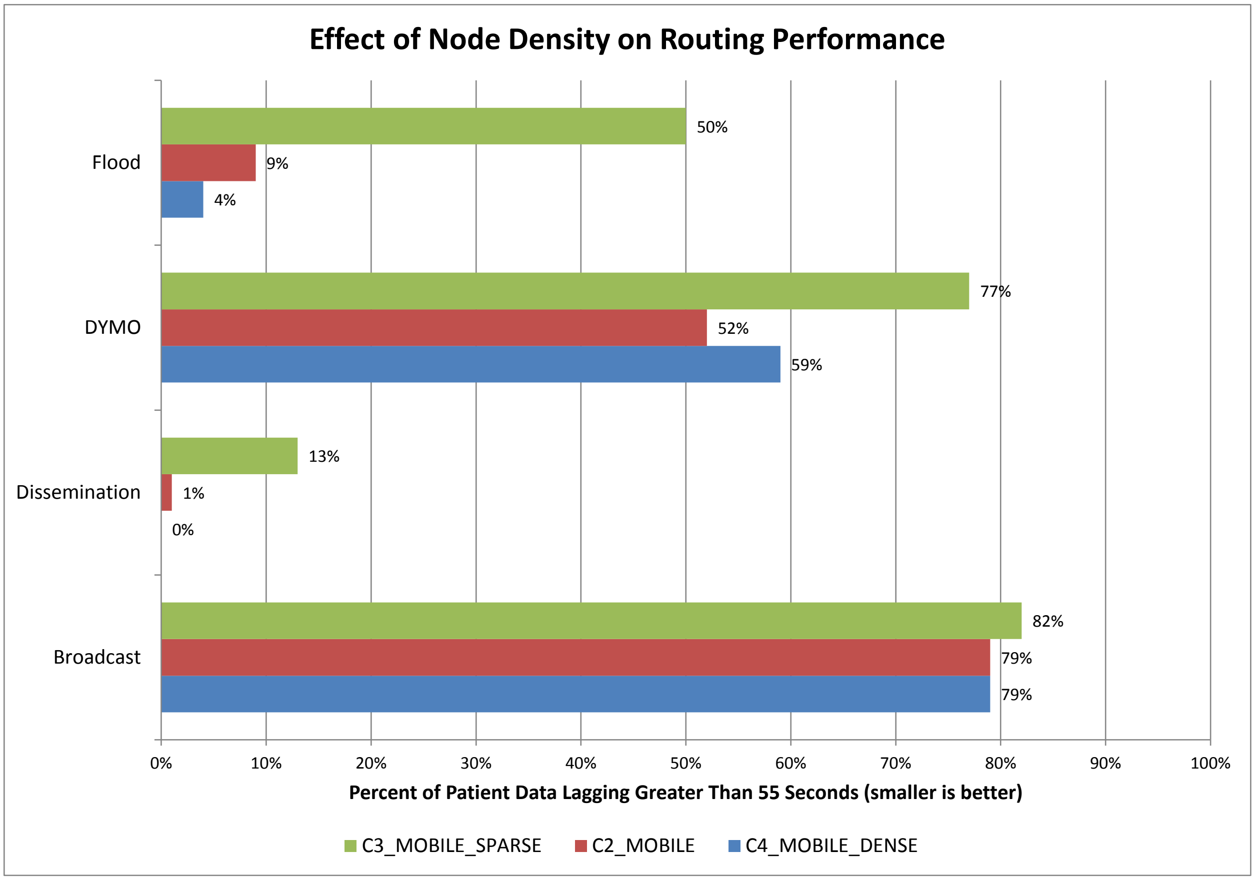

Figure 7. Effects of Node Density on Routing Method Performance

Figure 7 illustrates the importance of node density. Less dense simulations in which fewer nodes are randomly distributed over the same area will have decreased likelihood of generating multi-hop transfers. For the amount of data needing to be transferred, none of the simulations showed that flooding or dissemination techniques would be degraded by having too great a number of nodes within a small area, although there is certainly a limit, these tests do not indicate that there is a realistic limit that should be of concern for this application. The node density for the C2_MOBILE simulation, excluding the team leader, is 29 nodes over a 2500 m^2 area and the node density for the C3_MOBILE_SPARSE simulation 12 nodes over the same 2500 m^2 area. The performance in the latter case is undesirable, so use cases and operational scenarios should be considered to better understand the likely node densities that will occur in operational use. The effects of decreased node density could be directly mitigated by improved communication range.

6.0 RECOMMENDATIONS

The results clearly demonstrate the value of multi-hop networking for casualty monitoring in mass casualty events. The consistently good performance of the DRIP Dissemination protocol may even suggest that it could be incorporated in a vital sign sensing network without any further modification. However, it is likely that improvement could be made that take greater advantage of data muling as well as slightly more aggressive flooding and a mechanism for responder nodes to actively request updates to the oldest sets of patient data. These results also provide us with a way to estimate network performance of a given system with varying node densities. This can be used to make more informed design trades in the determination of transmission power, antenna design, and body placement. A better understanding of real world scenarios and their associated node densities, node mobility, and environments will be needed in order to facilitate the use of this approach in system design.

7.0 REFERENCES

[1] V. Shnayder, B.-r. Chen, K. Lorincz, T. Jones and M. Welsh, "Sensor networks for medical care," *Proceedings of the 3rd international conference on Embedded networked sensor systems - SenSys ’05,* p. 314, 2005.

[2] T. Gao, T. Massey, L. Selavo, D. Crawford, B.-r. Chen, K. Lorincz, V. Shnayder, L. Hauenstein, F. Dabiri, J. Jeng, A. Chanmugam, D. White, M. Sarrafzadeh and M. Welsh, "The Advanced Health and Disaster Aid Network: A Light-Weight Wireless Medical System for Triage," *IEEE Transactions on Biomedical Circuits and Systems,* vol. 1, no. 3, pp. 203-216, sep 2007.

[3] O. Chipara, W. G. Griswold and A. N. Plymoth, "A Measurement Study of Network Properties and Protocol Reliability during an Emergency Response".

[4] A. Faheem, R. Virrankoski and M. Elmusrati, "Improving RSSI based distance estimation for 802.15. 4 wireless sensor networks," *… Conference on Wireless …,* 2010.

[5] Texas Instruments, "CC2420 2.4 GHz IEEE 802.15.4 / ZigBee-ready RF Transceiver Datasheet," 2012.

[6] Helligso, Mikkelsen, Alroe and Esparza, "RSSI and LQI vs . Distance Measurement," no. May, 2011.

[7] J. Azevedo and F. E. Santos, "Signal Propagation Measurements with Wireless Sensor Nodes," pp. 1-24, 2007.

[8] Y. a. T. A. Chen, "On the implications of the log-normal path loss model: an efficient method to deploy and move sensor motes," *Proceedings of the 9th ACM Conference on Embedded Networked Sensor Systems,* pp. 26-39, 2011.

[9] H. Lee, A. Cerpa and P. Levis, "Improving wireless simulation through noise modeling," *Proceedings of the 6th international conference on Information processing in sensor networks - IPSN ’07,* p. 21, 2007.

[10] E. Miluzzo and X. Zheng, "Radio Characterization of 802 . 15 . 4 and Its Impact on the Design of Mobile Sensor Networks," pp. 171-188, 2008.

LIST OF SYMBOLS, ABBREVIAIOTNS, AND ACRONYMS

AODV	Adaptive On-Demand Distance Vector routing
DSR	Dynamic Source Routing
DTN	Delay Tolerant Networking
DYMO	Dynamic MANET On-demand routing
MANET	Mobile Adhoc NETwork